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BIG BANG NUCLEOSYNTHESIS CONSTRAINTS AND LIGHT ELEMENT ABUNDANCE ESTIMATES

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Abstract

To elucidate the significance of the effect of systematic uncertainties in light element abundance estimates on cosmological bounds derivable from Big Bang Nucleosynthesis (BBN) we present tables giving bounds on Ω_{baryon} and N_ν as one changes the limits on primordial ^{4}He and ^{7}Li. This allows us to derive new relations between these estimates and constraints on Ω_{baryon} and N_ν. For example, only if the helium mass fraction, $Y_p \geq .245$ does ^{7}Li (or D) presently play a role in placing an upper limit on the baryon density, and only if $Y_p \geq .250$ does ^{4}He cease to play a role in bounding η_{10}. All the elements combine together tend to give a stringent upper bound of 0.16 on Ω_{baryon}. We also find that Y_p must exceed .239 for consistency between theory and observation if D+^{3}He/H is less than 10^{-4}. Updated nuclear reaction rates, an updated neutron half life, Monte Carlo techniques, and correlations between the predicted abundances are incorporated in our analysis. We also discuss the handling of systematic uncertainties in the context of statistical analyses of BBN predictions.

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The theoretical analysis of BBN predictions for light element abundances has improved greatly in recent years, allowing in principle the derivation of very stringent constraints on various cosmological and particle physics parameters. Unfortunately however, the key factor in limiting the efficacy of this procedure is the reliability of the inferred light element primordial abundance estimates. Like many quantities based on astronomical observations, these are subject to large systematic uncertainties, many of which are difficult to accurately estimate.

In a recent work (Kernan and Krauss 1994, hereafter KK) we underscored the importance of considering such systematic errors when deriving BBN constraints by demonstrating that a comprehensive analysis which used the most up to date reaction rate uncertainties, and also incorporated quantitatively for the first time correlations between elemental abundances yielded, when compared with previously quoted observational upper limits on ^{4}He , $D +^3 He$, and ^{7}Li, embarassingly stringent limits on both the number of effective neutrino types and the present baryon density. Indeed, it was clear that standard BBN has a very limited range of consistency if systematic uncertainties in abundance estimates are not allowed for. While we argued that our results suggested the need for consideration of systematic uncertainties, this conclusion was not as widely quoted as were the limits we derived based on previous quoted abundance estimates which did not explicitly incorporate such uncertainties.

Subsequently, several groups have recently assessed more carefully the systematic uncertainties present particularly in the primordial ^{4}He abundance estimates (Olive and Steigman 1994, Copi, Schramm and Turner 1994, Sas-

selov and Goldwirth 1994), and have quoted various new upper limits on cosmological parameters based on their assessments. It is very clear, based in part on the differing estimates, that it is quite difficult at the present time to get an accurate handle on these uncertainties.

Because of this, and because we can utilize the full statistical machinery we previously developed when comparing predictions to "observations", we felt it would be useful to prepare a comprehensive table of constraints on N_ν and Ω_{Baryon} for a relatively complete range of different assumptions about light element abundances. In the first place such a table does not exist anywhere in the literature. Because of the interplay between various different elemental abundance constraints in deriving cosmological bounds, it is not possible to easily extrapolate previously existing limits, including our own, as abundance estimates are varied. Different groups which advocate different abundance limits can then only roughly translate these into bounds on Ω_B and N_ν. We hoped that a relatively complete tabulation of cosmological bounds as a function of abundance estimates would thus provide a useful reference for researchers. Next, the world average neutron half life value has just been updated to be $\tau_N = 887 \pm 2sec$ (Particle Data Group 1994), which results in a change in all BBN constraints. Our new tables thus update our previous results, besides expanding upon them. In addition, the present analysis allows us us to explore the role of different estimates in the constraints, as well as the effect of correlations as the light element abundance estimates vary. It also allows us to address several points which we feel are important to consider when deriving cosmological constraints using BBN predictions. Finally, this analysis leads to new simple relations between

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the light element abundances and limits on cosmological parameters such as the number of neutrinos[2], N_ν, and the baryon to photon ratio η_{10}, defined by $\Omega_B = .00366 h^{-2}(T/2.726)^3\eta_{10}$, where the Hubble constant is defined as $100h$ km/sec/Mpc.

BBN Predictions and Observations: Systematics, Correlations and Consistency

The chief developments of recent years which have affected the BBN predictions for light element abundances include: an updated BBN code, a more accurate measured neutron half life (Particle Data Group 1992,1994) and the determination of BBN uncertainties via Monte Carlo analysis; (Krauss and Romanelli 1990; Smith, Kawano and Malaney 1993). Most recently, we created (KK) an updated Monte Carlo code to account both for what was then the newest measured neutron half life, greater numerical accuracy (Kernan 1993) and also for new higher order effects in weak rates (Seckel 1993). The net effect of these changes is to both reduce the statistical error on the predicted value of Y_p, and also raise the predicted abundance by an η_{10}-independent factor of $+.0031$ compared to the value used in previous published analyses (Walker *et al* 1991; Krauss and Romanelli 1990). See KK for a more detailed description of our analysis.

We present here an updated figure for the predicted elemental abundances as a function of η_{10} (figure 1). However, as we stressed in KK, this standard figure should not be used alone to derive confidence limits on cosmological and particle physics parameters when comparing theoretical predictions and

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[2]We remind the reader that N_ν represents the effective number of relativistic degrees of freedom in the radiation gas during the BBN era, and is thus merely bounded below by the actual number of light neutrino species present in nature.

observations. Because the various elemental abundances are correlated deriving a limit using a single element throws out valuable information from other elements which, if incorporated, could lead to more stringent constraints. Stated another way, the predicted elemental abundances are generally not statistically independent. For example, there is a strong anti-correlation between Y_p and the remnant D $+^3$He abundance (the normalized covariance ranges from -0.7 to -0.4 in the η_{10} range of interest). Thus, if one generates 1000 predictions using a Monte Carlo scheme, those where the predicted ^{4}He is lower than the mean, which therefore may be allowed by some fixed observational upper bound Y_p, will also generally predict a larger than average remnant D$+^3$He/H abundance, which in turn could exceed the observational upper bound on this combination. Ignoring this correlation will result in a bound which is at the very least not statistically consistent. As we showed in KK, including such correlations in our analysis had a significant effect on limits on the number of neutrinos, and a less dramatic, but still noticable effect on limits on η_{10}.

Of course, if systematic uncertainties in the inferred primordial element abundances are dominant, one might wonder whether one need concern oneself with the proper handling of statistics in the predicted range. There is, after all, no well defined way to treat systematic uncertainties statistically. For example, should one treat a parameter range governed by systematic uncertainties as if it were gaussianly distributed, or uniformly distributed? The latter is no doubt a better approximation–i.e. a large deviation within some range may be as equally likely as a small deviation. But how should one handle the distribution for extreme values? Clearly it cannot remain

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uniform forever.

Thankfully, there are two factors which make the comparison of predictions and observations less ambiguous in the case of BBN:

(1) Because the allowed range in the observationally inferred abundances is much larger than the uncertainty in the predicted abundances, any constraint one deduces by comparing the two depends merely on the upper *or* lower observational limit for each individual element, and not only both at the same time. Thus, one is not so much interested in the entire distribution of allowed abundances as one is in one extremum of this distribution.

(2) Systematic uncertainties dominate for the observations, while statistical uncertainties dominate for the predictions.

Both of these factors suggest that a conservative but still well defined approach involves setting *strict* upper limits on Y_p, D+^{3}He, and ^{7}Li, and a lower limit on D, which incorporate the widest range of reasonably accepted systematic uncertainties. Determining what is reasonable in this sense is of course where most of the "art" lies. We will return to this issue shortly. Nevertheless, once such limits are set and treated as strict bounds, then one can compare correlated predictions with these limits in a well defined way. In this way one replaces the ambiguity of properly treating the distribution of observational estimates with what in the worst case may be a somewhat arbitrary determination of the extreme allowed observational values.

Clearly all the power, or lack thereof, in this procedure lies in the judicious choice of observational upper or lower limits. Because of our concern about the ability at present to prescribe such limits we present below results for a variety of them. Nevertheless, we do wish to stress that once one does choose

such a set, it is inconsistent not to use all of it throughout in deriving ones constraints. If one uses one observational upper limit for Y_p, for example, to derive constraints on the number of neutrinos, but does not use it when deriving bounds on the baryon density, then probably one has not chosen a sufficiently conservative bound on Y_p in the former analysis. It has been argued that a weak, logarithmic, dependence of Y_p on η_{10} invalidates its use in deriving bounds on the latter quantity. It is one of our more interesting conclusions that not only can this argument be somewhat misrepresentative for an interesting range of Y_p values, but that until Y_p exceeds statistically derived upper limits by a large amount, it can continue to play a signifcant role in bounding η_{10} from above. (Note that the lower bound on η_{10} is presently governed by the observational upper limit on the D+^{3}He. For a discussion of this bound on η_{10} see KK and (Krauss and Kernan 1994).

Before proceeding to give our results, we briefly outline the rationale for the range of limits on light element abundances we choose to explore here.

Abundance Estimate Uncertainties:The Range

It is beyond the scope of this work to examine in detail the observational uncertainties associated with the determination of primordial light element abundances. Our purpose instead is to exploit recent observational and theoretical estimates of these uncertainties in order to examine how BBN constraints will be affected by incorporating such uncertainties. Thus we merely provide here a very brief review of the recent literature. The reader is referred to the cited papers and references therein for further details.

(a) ^{4}He: By correlating ^{4}He abundances with metallicity for various heavy elements including O,N and C, in low-metallicity HII regions one can attempt

to derive a "primordial" abundance defined as the intercept for zero metallicity. This can be determined by a best fit technique, assuming some linear or quadratic correlation between elemental abundances (i.e. see Peimbert, and Torres-Peimbert 1974; Pagel,Terlevich and Melnick 1986; Pagel, Simonson, Terlevich,and Kennicutt 1992; Walker *et al* 1991). The statistical errors associated with such fits are now small. Best fit values obtained typically range from .228-.232, with statistical "1σ" errors on the order of .003-.005. This argument yields the upper limit of .24 (Walker *et al* 1991) which has been oft quoted in the literature. Recently this number has begun to drift upwards slightly. New observations of HII regions in metal poor galaxies have tended to increase the statistically derived zero intercept value of Y_p by perhaps .005 (i.e. (Skillman et al 1993, Olive and Steigman 1994)). In addition, the recognition that systematic, and not statistical uncertainties may dominate any such fit has become more widespread recently. The key systematic uncertainty which interferes with this procedure is the uncertainty in the ^{4}He abundance determined for each individual system, based on uncertainties in modelling HII regions, ionization, etc used to translate observed line strengths into mass fractions. Many observational factors come into play here (see (Skillman et al 1994) for a discussion of observational uncertainties), and people have argued that one should add an extra systematic uncertainty of anywhere from .005-.015 to the above estimate. Clearly thus, one should examine implications of ^{4}He abundances in the range .24-.25. We shall show that for Y_p above .25; (a) ^{4}He becomes unimportant for bounding η_{10}, and (b) the effect on bounds on N_ν can be obtained by straightforward extrapolation from the data obtained for the range .24-.25.

(b) ^{7}Li: It is by now generally accepted that the primordial abundance of ^{7}Li is closer to the Spite Pop II plateau than the Pop I plateau. Nevertheless, even if one attempts to fit the primordial abundance by fitting evolutionary models to the Pop II data points (Deliyannis *et al* 1989), assuming no depletion, one still finds an 2σ upper limit as large as 2.3×10^{-10}. The role of rotationally induced depletion is still controversial. It is clear some such depletion is expected, and can be allowed for (Pinsonneault, Deliyannis and Demarque 1992), but observations of ^{6}Li, which is more easily depleted, put limits on the amount of ^{7}Li depletion which can be allowed. We will assume an extreme factor of 2 depletion as allowable, and thus we explore how cosmological bounds are affected by a ^{7}Li upper limit as large as $\approx 5 \times 10^{-10}$.

(c) D and D+^{3}He: We take the solar system D abundance of 2×10^{-5} as a safe firm lower bound on D, and the previously quoted upper limit of 10^{-4} as a firm upper limit on D+^{3}He (Walker *et al* 1991). The recent Songaila *et al* (1994) result for D (see also (Carswell *et al* 1994) , which is larger than this upper limit, is in apparent conflict with another similar measurement, and with estimates of the pre-solar D+^{3}He abundance, and there are preliminary reports of contradictory data taken along other lines of sight. In any case, the dramatic change in BBN limits should the former result be confirmed is discussed in great detail in (Krauss and Kernan 1994), so we do not discuss this possibility further here.

Results and Analysis

Tables 1-3 give our key results. The data were obtained using 1000 Monte Carlo BBN runs at each value of η_{10}, with nuclear reaction rate input parameters chosen as Gaussian random variables with appropriate widths (see

KK for details). In each case the number of runs which resulted in abundances which satisfied the joint constraints obtained by using combinations of the upper limits on ^{4}He, ^{7}Li, and D+^{3}He or the lower limit on D was determined. Limits on parameters were determined by varying these until less than 50 runs out of 1000 (up to $\sqrt{N}$ statistical fluctuations) satisfied all of the constraints.

Table 1 displays the upper limit on N_ν for various values of Y_p. As is shown, this was governed by the combination of ^{4}He and D+^{3}He upper limits. Shown in the table are the number of acceptable runs out of 1000 when the two elemental bounds are considered separately and together, for an η_{10} range which was found to maximize the number of acceptable models. Throughout the Y_p^{max} region from .24 to .25, both the Y_p and D+^{3}He limits play a roughly equal role in determining the maximum value of N_ν. We are able to find a remarkably good analytical fit for the maximum value of N_ν as a function of Y_p as follows:

$$N_\nu^{max} = 3.07 + 74.07(Y_p^{max} - .240) \qquad (1)$$

The linearity of this relation is striking over the whole region from .24 to .25 in spite of the interplay between the two different limits in determining the constraint. Note also that this relation differs from than that quoted in Walker *et al* (1991) between Y_p and N_ν in that the slope we find is about 13% less steep than that quoted there. The two formulae are not strictly equivalent in that the one presented in Walker *et al* (1991) presented the best fit value of Y_p determined in terms of N_ν, while the present formula gives a relation between the maximum allowed values of these parameters, based on limits on the *combination* Y_p and D+^{3}He, and on the width of the

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predicted distribution. In this sense, eq. (1) is the appropriate relation to utilize when relating bounds on Y_p to bounds on N_ν.

Tables 2 and 3, which display the upper bounds on η_{10}, are perhaps even more enlightening. They demonstrate the senitivity of the upper limit on η_{10} and hence Ω_{baryon} to the various other elemental upper limits as Y_p is varied. Several features of the data are striking. First, note that ^{4}He completely dominates in the determination of the upper limit on η_{10} until Y_p =.245, even for the most stringent chosen upper limit on ^{7}Li. If this limit on ^{7}Li is relaxed, then ^{4}He dominates as long as the upper limit on Y_p $\leq$.248! Also note that the "turn on" in significance of the ^{7}Li contribution to the constrain is somewhat more gradual than the "turn off" of the ^{4}He constraint. The former turns on over a range of η_{10} of about 2, while the latter turns off over a range of about 1-1.5. This gives one some idea of the size of the error introduced in determining upper bounds by using only either element alone, rather than the combination. Next, for a Y_p upper limit which exceeds .248, the lower bound on D begins to become important. It quickly turns on in significance so that by the time the upper limit on Y_p is increased to .25, ^{4}He essentially no longer plays a role in bounding η_{10}. Finally, note that both the relaxed bound on ^{7}Li and the D bound converge in significance at about the same time, so that for $\eta_{10} > 7.25$, both constraints are significantly violated. This implies a "safe" upper limit on η_{10} at this level, which corresponds to an upper bound $\Omega_{baryon} \leq .163$, assuming a Hubble constant in excess of 40 km/sec/Mpc. We again stress that a value this large is only allowed if Y_p exceeds .250. If, for example, $Y_p \leq .245$, then the upper bound on Ω_{baryon} is essentially completely determined by ^{4}He and is then at most 0.11.

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These limits may be compared to recent estimates of Ω_{baryon} based on X-ray determinations of the baryon fraction in clusters (White *et al* 1993).

One final comment on the role of Y_p in constraining η_{10}: It has been stressed that because of the logarithmic dependence of the former on the latter, that Y_p cannot be effectively used to give a reliable upper bound on η_{10}. This is somewhat deceptive, however. We can compare how much more sensitive the bound on η_{10} is to Y_p than the bound on N_ν is by making a linear fit to the former relation and comparing it to (1). If we do this, we find first that the linear fit is quite good out to Y_p as large as .245 (after which a quadratic fit remains good all the way out to .248, where the D and relaxed ^{7}Li bounds begin to take over), and is given by

$$\eta_{10}^{max} \approx 3.22 + 354(Y_p^{max} - .240) \tag{2}$$

Seen in these terms, the η_{10} upper limit is approximately 4.5 times more sensitive to the precise upper limit chosen for Y_p than is the N_ν upper limit. Thus, while there is no doubt that varying the upper limit on Y_p has a more dramatic effect on the upper bound one might derive for η_{10} than it does for constraining N_ν, the quantitative nature of the relative sensitivities is perhaps displayed, for the relevant range of Y_p, by comparing the linear approximations presented here than by discussing logarithmic vs linear dependencies. More important, even recognizing the increased sensitivity of η_{10} on Y_p, unless one is willing to accept the possibility of a rigid upper bound on Y_p greater than .247, it is overly conservative to ignore ^{4}He when deriving BBN bounds on η_{10}.

Finally, we update one other quantity of importance for the comparison of BBN predictions with observations: the minimum value of Y_p such that

BBN predictions are consistent with observation. We explored the range of η_{10} allowed at the 95% confidence level (i.e. 50 out of 1000 models) as the value of $Y_p{}^{max}$ was reduced. For $Y_p \leq .239$ no range of η_{10} was allowed when this constraint was combined with the D + ^{3}He bound. Previously we derived a lower bound on Y_p of .238 if D+^{3}He was used alone to first bound η_{10}, and then the η_{10} value was used to bound Y_p (to compare to earlier such bounds (i.e. (Krauss and Romanelli 1990)). The new neutron half life would not change that bound. However in any case the newly derived bound of .239 obtained using the correlated constraints is more stringent, and more consistent. If the primordial helium abundance is determined empirically to be less than this value with great confidence, and the D + ^{3}He upper limit remains stable, standard BBN would be inconsistent with observation.

Conclusions: There can be little doubt that the present ability of BBN to constrain cosmological parameters is almost completely governed by systematic uncertainties in our inferences of the actual light element primordial abundances. Nevertheless, the fact that such systematic uncertainties need not be gaussian does not block our ability to utilize the statistically meaningful uncertainties in BBN predictions. As long as we are willing to quote conservative one-sided limits on the various abundances which incorporate reasonable estimates of the systematic uncertainties then the determination of what confidence levels can be assigned to various theoretical predictions is straightforward. Moreover, as the observational limits on various elemental abundances is varied, the significance of the different elements for constraining cosmological parameters varies. In addition, for a non-trivial range in η_{10}, correlations exist between the various abundance predictions, and a self

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consistent use of all available constraints is important. Finally, Y_p, in spite of its systematic uncertainty, plays a dominant role unless one is willing to accept an upper limit of greater than .247. Beyond that, the convergence of D and ^{7}Li limits suggest a safe upper bound of on the baryon density today of less than 16% of closure density.

As time proceeds and more independent observations are made we will undoubtedly get a better handle on the systematic uncertainties which presently limit the efficacy of BBN constraints. Until then, the updated tables and relations presented here should provide a useful reference to allow researchers to translate their own limits on the light element abundances into meaningful bounds on N_ν and η_{10}.

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Table 1: ^{4}He Abundance Estimates & N_ν limits

Y_p	$N_{\nu_{max}}$	# allowed models: $\{^4\text{He \& [D+}^3\text{He]}\}(^4\text{He:D+}^3\text{He})$			
		$\eta_{10}=2.75$	2.80	2.85	2.90
.240	3.07	40(603:148)	52(429:254)	46(268:376)	38(170:534)
		$\eta_{10}=2.80$	2.85	2.90	2.95
.241	3.14	38(532:171)	46(354:309)	39(219:470)	35(131:625)
.242	3.21	41(562:154)	55(451:276)	53(272:423)	52(163:616)
.243	3.29	17(588:110)	32(410:220)	46(266:378)	36(184:513)
.244	3.36	30(669:102)	44(501:187)	38(353:336)	40(216:464)
		$\eta_{10}=2.85$	2.90	2.95	3.00
.245	3.43	50(598:173)	68(449:296)	64(308:427)	54(173:586)
.247	3.59	27(635:84)	30(480:184)	47(338:306)	39(185:488)
		$\eta_{10}=2.95$	3.00	3.05	3.10
.250	3.82	45(491:207)	47(364:374)	50(225:495)	32(131:587)

Table 2: ^{4}He and ^{7}Li Abundance Estimates & η_{10} limits

$Y_{p_{max}}$	$\eta_{10_{max}}$ $(^7\text{Li}_{-10} < 2.3)$	# allowed models: $\{^4\text{He \& }^7\text{Li}\}$ $(^4\text{He:}^7\text{Li})$	$\eta_{10_{max}}$ $(^7\text{Li}_{-10} < 5)$	# allowed models: $\{^4\text{He \& }^7\text{Li}\}$ $(^4\text{He:}^7\text{Li})$
.240	3.26	56 (60:998)	3.26	56 (60:1000)
.241	3.55	45 (45:986)	3.55	45 (45:1000)
.242	3.89	45 (47:905)	3.89	47 (47:1000)
.243	4.26	50 (60:626)	4.27	46 (46:1000)
.244	4.64	48 (92:296)	4.71	49 (49:1000)
.245	5.01	45 (211:118)	5.23	62 (62:984)
.246	5.23	51 (679:62)	5.80	46 (50:810)
.247	5.25	52 (997:52)	6.36	48 (80:500)

Table 3: ^{4}He, D and ^{7}Li Estimates & η_{10} limits ($^7\text{Li}_{-10} <5$; $D_{-5} > 2$)

$Y_{p_{max}}$	$\eta_{10_{max}}$	# allowed models: $\{^4\text{He \& D \& }^7\text{Li}\}$ $(^4\text{He \& D:}^4\text{He \& }^7\text{Li:D \& }^7\text{Li})$ $(^4\text{He:D:}^7\text{Li})$		
.248	6.94	48 (136:53:156) (178:516:203)		
.249	7.22	52 (177:101:64) (654:217:136)		
.250	7.24	47 (191:113:47) (995:191:113)		

Figure Captions

Figure 1: BBN Monte Carlo predictions as a function of η_{10}. Shown are symmetric 95% confidence limits on each elemental abundance.
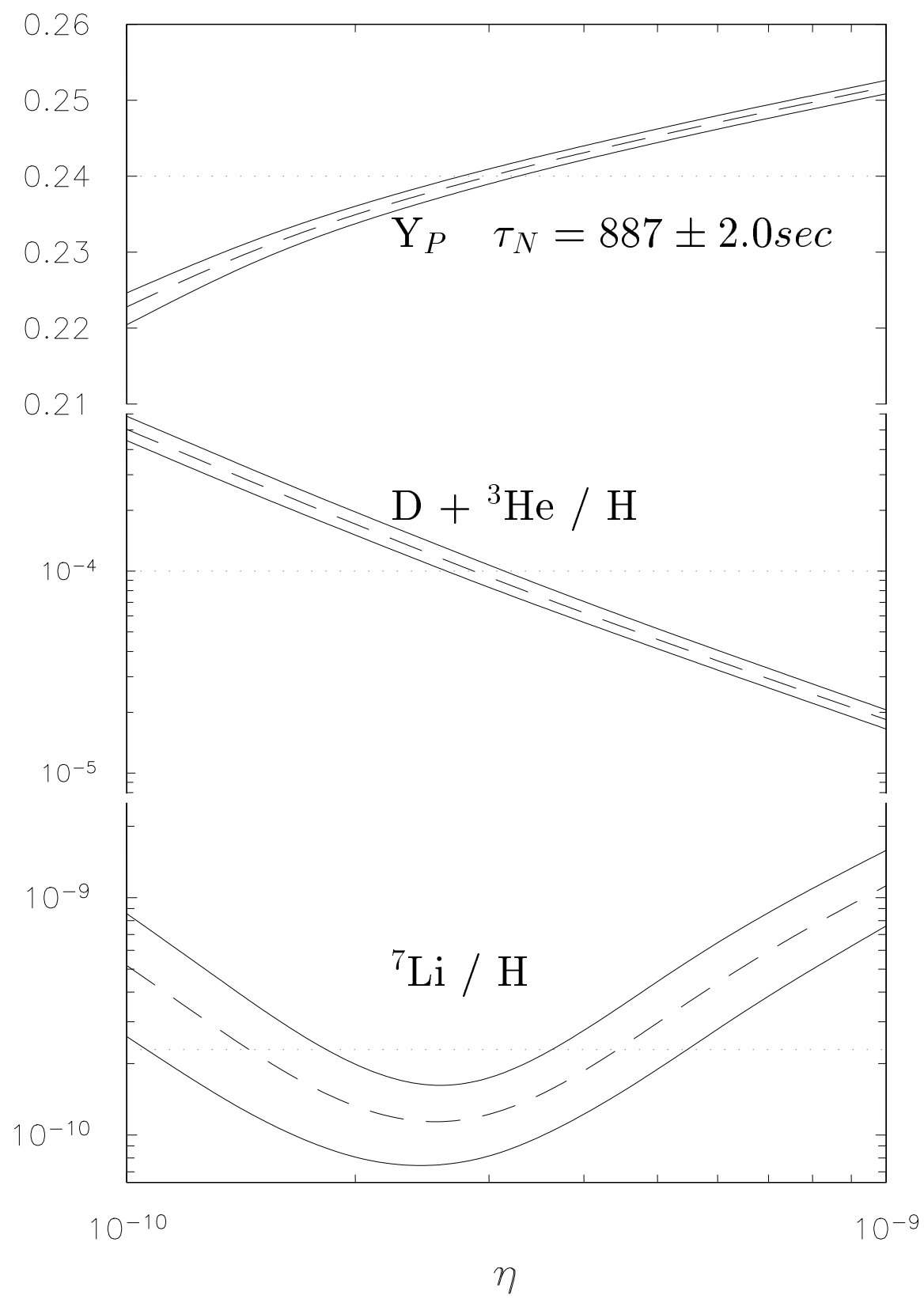
Figure 1

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